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Advanced Dry-cooling with Integrated Enhanced Air-Cooled Condenser and Daytime Load-shifting Thermal Energy Storage for Improved Power-Plant Efficiency

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Background / Motivation

- Large parts of the US are expected to experience water stress over the next two decades.
- Need disruptive technologies to reduce water usage in one of the largest consumers of fresh water (wet cooling for electricity generation).
- Make dry-cooling systems (ACCs) more effective:
  - Enhance the low air-side heat transfer coefficient and reduce footprint.
  - Mitigate the thermodynamic limitations on performance when daytime peak ambient temperatures are high.
Background / Motivation

Impact of limitations due to high daytime ambient temperature on dry- or air-cooling in fossil fuel power plants:

- ACCs are over-sized with a large initial temperature difference (ITD); condenser pressure is correspondingly higher.
- Increases both capital cost and operating cost.
- Yields low Rankine cycle thermodynamic efficiency at peak period of electricity demand.
Technology Innovation

- Air-cooled condenser (ACC) with novel enhanced surfaces
- Inlet-air pre-cooling asynchronous thermal energy storage (TES) system
ACC Performance Enhancement –
Reduce Size of ACC (based on fixed power and pressure drop constraint)

Fixed pressure drop constraint
(fixed heat transfer rate)

\[ \Delta p = f \left( \frac{4L}{d_h} \right) \left( \frac{\rho u_m^2}{2} \right) = \left( \frac{2\mu^2 L}{\rho d_h^3} \right) \left( f \text{Re}^2 \right) \]

\[ \left( f \text{Re}^2 \right)_{PF} = \left( f \text{Re}^2 \right)_{EF} \]

\[ Q = (UA)\Delta T_m \approx \left( hA \right)_{air} \Delta T_i = \left( kP_iNL\Delta T_i/d_h \right) Nu \]

\[ \left( A_{EF} / A_{PF} \right) = \left( \frac{\text{NTU}_{PF}}{\text{NTU}_{EF}} \right)_{Q,\Delta T,\Delta p,d_h} = \left( h_{PF} / h_{EF} \right)_{Q,\Delta T,\Delta p,d_h} \]
ACC Performance Enhancement –
Reduce Size of ACC (based on fixed power and pressure drop constraint)
## TES Design and Performance –
Phase-Change Material (PCM) Selection; Salt Hydrates

<table>
<thead>
<tr>
<th>PCM</th>
<th>$T_{sf}$ [°C]</th>
<th>$\Delta T_{sc}$ [°C]</th>
<th>$h_{sf}$ [kJ/kg]</th>
<th>$h_{sf}$ [kJ/m$^3$]</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithium Nitrate Trihydrate</td>
<td>29.2</td>
<td>3.8</td>
<td>273</td>
<td>650</td>
<td></td>
</tr>
<tr>
<td>Calcium Chloride Hexahydrate</td>
<td>29.8</td>
<td>5.9</td>
<td>182</td>
<td>311</td>
<td>High Corrosion</td>
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<tr>
<td>Zinc Nitrate Hexahydrate</td>
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<td>3.1</td>
<td>140</td>
<td>290</td>
<td>High $T_{sf}$</td>
</tr>
<tr>
<td>Sodium Sulfate Decahydrate</td>
<td>32.2</td>
<td>25.2</td>
<td>233</td>
<td>341</td>
<td>Unstable</td>
</tr>
</tbody>
</table>
TES Design and Performance –
PCM (LiNO$_3$·3H$_2$O) Stable Thermal-Cycling Performance

Stability of thermal capacity of LiNO$_3$·3H$_2$O over 1000 heating (dehydrating) and cooling (rehydrating) cycles

Self-seeded nucleation and phase-transition stability of LiNO$_3$·3H$_2$O during thermal cycling
Lab-Scale (100 kJ) TES Module Design and Performance

- TES PCM Encapsulation Matrix
  - Low-cost wire mesh fins for PCM channel
- Coolant Passages
  - Offset fin provides heat transfer enhancement in liquid passages

100 kJ Lab-Scale Prototype TES HX
Project Objectives

Develop (design, test, and scale up) a novel transformative air-cooling system which integrates a PCM-based thermal energy storage (TES) for pre-cooling of ambient inlet air to the air cooled condenser (ACC) during peak daytime hours, via a liquid coolant-to-air pre-cooler heat exchanger (ACHX)

- Task 1: Project Management and Planning
  - Overall management of the project as per the Project Management Plan -- UC

- Task 2: Design and Performance Evaluation of TES System
  - Design optimization of TES, Lab testing, and Scale up – UC, Evapco, EPRI

- Task 3: Design and Performance Evaluation of Air Pre-cooler
  - Design optimization and performance evaluation and Scale up – UC, Evapco, EPRI

- Task 4: Technology Demonstration
  - Fabrication and testing of pilot-scale system - EPRI

- Task 5: Techno-Economic Analysis
  - TEA Analysis – UC, Maulbetsch, Evapco, EPRI
Preliminary TES Scale-up & Testing with Air Pre-Cooler

1.0 MJ TES + ACHX – with Air-Side diurnal temperature variations

Inlet air – models diurnal temperature variation (Max 106°F, Min 74°F over a two-hour cycle)

Heating: 1 MJ over 40 min period; Cooling: 1 MJ over 80 min period; Air Pre-Cooler tube-fin heat exchanger size: ~ 420 W (or ~ 450 W, or can be overdesigned for testing purposes)

Total time: 2 hours

TES scale-up (10× scale-up; 100 kJ → 1.0 MJ) and performance testing
  • Performance with diurnal air-side temperature variations (system-level prototype performance)
TES (1.0 M) HX and Air Pre-Cooler Test Results
NEXT STEPS: TES Scale-up & Testing with Air Pre-Cooler

1.0 MJ TES + ACHX – with Air-Side diurnal temperature variations

- TES (1 MJ) redesign and performance testing
- Performance with diurnal air-side temperature variations (system-level prototype performance)

- Optimized Redesign of TES – consider an enclosed (brazed or welded) tube-fin heat exchanger and/or a semi-brazed and gasketted plate-and-frame heat exchanger.
- Reconfigure laboratory test set up and establish testing protocols for the redesigned TES coupled with air pre-cooler.
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